Russian-German Cooperation SYSTEM LAPTEV SEA:

The Expedition COAST I:
COAST Drilling Campaign 2005:
Subsea permafrost studies in the near-shore zone of the Laptev Sea

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Contents

The Expedition COAST I

1. Background and Objectives

One of the main foci of the new Laptev Sea System Project "Dynamics of Permafrost" is the evolution of the sub-sea permafrost within the near-shore zone of the shallow shelf. Studies of permafrost evolution in the coastal zone allow us to understand the on-shore/off-shore permafrost system evolution more precisely. Within the framework of Russian-German cooperation, relatively deep drilling by a commercial drilling team was conducted in the spring of 2005. There are only a few drilling transects within the shore face profile of the Asian Arctic Seas. Previous transects were drilled from the sea ice in spring or from small drilling platforms. As usual for the shallow Laptev Sea shelf with its thermal abrasion coastline, the sub-sea permafrost table is found by drilling to depths of 5-60 metres. The formation of new sub-sea permafrost has occasionally been observed in the shallows, in association with bottom accumulative deposits (Grigoriev N. F., 1966).

The COAST expedition sought to recover permafrost material in a transect spanning the onshore and offshore domains horizontally, and reaching from surface material to as great a depth as possible, in a region of the Laptev Sea coast minimally affected by fluvial and deltaic deposition. The recovered material thus provides for a temporal sequence of changes in permafrost since at least the last transgression. The Laptev Sea coast is heavily affected by erosion and can be regarded as a natural laboratory for coastal evolution. The region between the Olenyek and Anabar River deltas (Cape Mamontov Klyk) was selected, since the influence of fluvial waters and deltaic deposition generally decreases with distance from the river deltas. Cores were drilled along a 12 km transect from terrestrial permafrost to offshore, marine-affected permafrost. The transformation from terrestrial to submarine permafrost in the western and central Laptev Sea region can be studied using this material.

The coastal drilling transect campaign was originally planned for the spring of 2004, but was delayed until the spring of 2005 due to problems obtaining research permits. Investigations completed during the first two years concentrated therefore on the evaluation of available sample material, which had been obtained during preliminary investigations. Permafrost drilling took place at Cape Mamontov Klyk in the spring of 2003. In the summer of 2003 the expedition "Lena-Anabar 2003" led to extensive field work, including the morphology and bathymetry of the coring locations and extensive sampling (Schirrmeister et al., 2004).

The temporal and spatial variability of permafrost thickness and distribution in the Laptev Sea is closely coupled to global Quaternary climatic cycles. Since the region was hardly glaciated, cold, deep terrestrial permafrost developed on the shelf during cold-period marine regressions. During interglacial periods, marine transgressions flooded the continental shelf. The offshore, terrestrial, permafrost sediments were inundated and fell under marine influence. The effects of flooding on permafrost are still poorly understood. It is accepted that changes in the thermal regime at the sediment surface, the geocryological structure of the sediments, and, in particular, pore water salinity play a crucial role. In the nineteen-seventies, several American and Russian authors reported on and investigated submarine permafrost and salinity profiles (Ponomarev 1950, Antipina et al. 1981, Soloviev 1981, Telepnev 1981, Zhigaev 1981, Romanov & Kunitsky 1985, Fartyshev 1993*)* This work aims at expanding on these studies in a co-operative effort between European and Russian scientists.

Acknowledgements

The success of the COAST Drilling Campaign 2005 would not have been possible without the help of the Tiksi Hydrographical Base team, which organized field transportation: Dmitry Melnichenko (chief), Victor Dobrobaba, Vladimir Yakshin, Timophey Sidorov, Alexander Saphin, Yuri Tyazhelukhin, Yuriy Vlasov and Sergey Kamanin, and the Yakutsk Geological Prospect-Survey Expedition, Drilling Department team: Vitaly Makagonov (chief), Sergey Gladchenko, Valerie Ternovoy, Vladimir Kobzev, Valerie Dodonov and Mikhail Skuratov (drilling crew).

The COAST I expedition was a contribution to the joint research project “Process studies of permafrost dynamics in the Laptev Sea” (project number 03G0589) funded by the German federal ministry of Education and Research (BMBF) as well as to the Russian German Science Cooperation “SYSTEM LAPTEV SEA”:

Figure 1: Drilling camp on the sea ice just offshore of the Cape Mamontov Klyk coastline. The expedition took place in April 2005

2. Logistics and itinerary

Due to problems obtaining research permits, the drilling activities for COAST had to be shifted from the spring of 2004 to the spring of 2005. Since the drilling campaign took place one year later than originally planned, analyses of the recovered sediment material are still under way. A variety of data is available however, including descriptions of the extent of material recovered and its thermal, cryogenic, geochemical and lithological characteristics.

Details of the itinerary, participating institutions and expedition participants are listed in Tables 1 to 3. Field work was accomplished through the use of an equipment caravan traveling over the sea ice to the drilling location. The drilling rig, well tubes, bore casing and additional equipment were delivered from Yakutsk to Tiksi by two cargo air-freighters (AN-12). The expeditionary transport caravan consisted of a sledge-tractor train, including two caterpillar tractors (S-160), a cross-country vehicle (GAZ-71), the drill rig (URB-2A-2) on skids, two two-storied mobile-homes (baloks) and three cargo snow-sledges with various equipment, diesel oil, and bore casings, etc. The caravan started from Tiksi on March 28, 2005. The journey lasted two weeks, and mainly followed river and sea ice through the Lena Delta and then across Olenyek Bay. The thickness of sea ice ranged between 1.7 and 2.1 m. The scientific team, excluding M. Grigoriev, flew by MI-8 helicopter on April 11 to join the caravan.

The scientific team of the expedition consisted of 6 members: Volker Rachold, Waldemar Schneider (AWI-Potsdam, Germany), Ralf Junker (University Bremen, Germany), Mikhail Grigoriev, Viktor Kunitsky (Permafrost Institute, Yakutsk, Russia) and Dmitriy Bolshiyanov (AARI, St-Petersburg, Russia).

During the journey to Cape Mamontov Klyk and back, the transport team encountered serious obstacles in the form of sea ice cracks, hummocks, snowdrifts and sand storms on the ice. Not far from the Olenyek Delta, the engine of one of the caterpillar tractors broke and the transport team had to wait a few days for a new tractor (S-130) from Tiksi. Early in the morning of April 11 the sledge-tractor train reached its destination point – Cape Mamontov Klyk. The length of the route (Tiksi - Cape Mamontov Klyk) was more than 500 km. The total weight of the sledge-tractor train was more than 130 tons.

Table 1: List of participants

Name	e-mail	Institution
Dmitriy Bolshiyanov	bolshiyanov@aari.nw.ru	AARI
Victor Dobrobaba	baza@tiksi.sakha.ru	THB
Valerie Dodonov	lengeo@mail.sakha.ru	YGPSE
Sergey Gladchenko	lengeo@mail.sakha.ru	YGPSE
Mikhail Grigoriev	grigoriev@mpi.ysn.ru	PIY
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Sergey Kamanin	baza@tiksi.sakha.ru	THB
Vladimir Kobzev	lengeo@mail.sakha.ru	YGPSE
Viktor Kunitsky	kunitsky@mpi.ysn.ru	PIY
Volker Rachold	volker.rachold@iasc.se	AWI
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Timophey Sidorov	baza@tiksi.sakha.ru	THB
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Valerie Ternovoy	lengeo@mail.sakha.ru	YGPSE
Yuri Tyazhelukhin	baza@tiksi.sakha.ru	THB
Yuriy Vlasov	baza@tiksi.sakha.ru	THB
Vladimir Yakshin	baza@tiksi.sakha.ru	THB

Table 2: List of participating institutions

AARI	Arctic and Antarctic Research Institute, Bering St. 38, 199397 St. Petersburg, Russia
AWI	Alfred Wegener Institute, Research Unit Potsdam, PO Box 60 0149, D-14401 Potsdam, Germany
PIY	Permafrost Institute, Russian Academy of Science, 677018 Yakutsk, Yakutia, Russia ul. Merzlotnaya 36
THB	Tiksi Hydrographical Base, Tiksi, Yakutia, Leninskaya St., 15
UB	Department of Geosciences, University of Bremen, Postfach 330440, 28334 Bremen, Germany
YGPSE	Yakutian Geological Exploring-Survey Expedition: 677014, Russia, Yakutsk, Kalvits Str, 34, Yakutian Geological Exploring-Survey Expedition

Figure 2: Expedition team, including the drilling crew, tractor drivers and the cook. Expedition participants were: Dmitriy Yuryevich Bolshiyanov, Mikhail Nikolayevich Grigoryev, Victor Vladimirovich Kunicki, Valerie Anatoljevich Ternovoy, Vladimir Nikolayevich Kobzev, Sergey Ivanovich Gladchenko, Valerie Ivanovich Dodonov, Mikhail Garikovich Skuratov, Victor Vasiljevich Dobrobaba, Vladimir Nikolayevich Yakshin, Timofey Nikolayevich Timofeev, Aleksandr Nikolayevich Safin, Yuri Vladimirovich Tyazhelukhin, Volker Rachold, Waldemar Schneider, and Ralph Junker (plus one unnamed participant).

Figure 3: Drilling platform and support vehicles on the ice

Table 3: COAST Expedition Itinerary

Date	Activity
23.03.2005	Cargo flight (AN-12) from Yakutsk to Tiksi (well tubes, boring casing and various equipment).
26.03.2005	Cargo flight (AN-12) from Yakutsk to Tiksi (drilling rig): M. Grigoriev, S. Gladchenko, V. Ternovoy, V. Kobzev, V. Dodonov, M. Skuratov.
28.03.2005	Departure from Tiksi (sledge-tractor train): M. Grigoriev, S. Gladchenko, V. Ternovoy, V. Kobzev, V. Dodonov, M. Skuratov, V. Dobrobaba, V. Yakshin, T. Sidorov, A. Saphin, Yu. Tyazhelukhin, S. Kamanin.
5.04.2005	Departure from Tiksi (additional caterpillar tractor instead of destroyed near Olenyek Delta): Yu. Vlasov.
5.04.2005	Flight from Berlin (Schoenefeld) to Moscow (Domodedovo): V. Rachold, W. Schneider, R. Junker.
6.04.2005	Flight from Moscow (Domodedovo) to Yakutsk: V. Rachold, W. Schneider, R. Junker, D. Bolshiyanov.
7.04.2005	Flight from Yakutsk to Tiksi: V. Rachold, W. Schneider, R. Junker, D. Bolshiyanov, V. Kunitsky.
11.04.2005	Arrival of Sledge-tractor train at Mamontov Klyk Cape.
11.04.2005	Flight by helicopter MI-8 from Tiksi to Mamontov Klyk Cape: V. Rachold, W. Schneider, R. Junker, D. Bolshiyanov, V. Kunitsky.
26.04.2005	Return flight by helicopter MI-8 from Mamontov Klyk Cape to Tiksi: M. Grigoriev, V. Rachold, W. Schneider, R. Junker, D. Bolshiyanov, V. Kunitsky, Yu. Tyazhelukhin.
27.04.2005	Departure from Mamontov Klyk Cape (sledge-tractor train): S. Gladchenko, V. Ternovoy, V. Kobzev, V. Dodonov, M. Skuratov, V. Dobrobaba, V. Yakshin, T. Sidorov, A. Saphin, Yu. Tyazhelukhin, S. Kamanin, Yu. Vlasov.
28.04.2005	Flight from Tiksi to Yakutsk: M. Grigoriev, V. Rachold, W. Schneider, R. Junker, D. Bolshiyanov, V. Kunitsky.
29.04.2005	Flight from Yakutsk to Moscow (Domodedovo): V. Rachold, W. Schneider, R. Junker, D. Bolshiyanov.
30.04.2005	Flight from Moscow (Domodedovo) to Berlin (Schönefeld): V. Rachold, W. Schneider, R. Junker.
9.05.2005	Arrival of aledge-tractor train in Tiksi.
11.05.2005	Flight from Tiksi to Yakutsk: S. Gladchenko, V. Ternovoy, V. Kobzev, V. Dodonov.
15.05.2005	Cargo flight (AN-12) from Yakutsk to Tiksi (drilling rig): M. Skuratov.

3. Field Methods and Sample Recovery

3.1 Coring

The COAST expedition used a drilling rig (URB-2A-2) with a hydraulic rotary-pressure mechanism. Depending on sediment characteristics, it is capable of drilling bore holes up to 250-300 m deep. Well tubes and bore casings (liners) from 1.5 to 4 m length and from 70 to 160 mm (89, 108, 127 and 146) diameter were used during drilling. Casing size decreased with penetration depth and lined the complete borehole. Nevertheless there were some problems with water infiltration in the bore holes, sometimes even within the frozen stratum of sub-sea sediment. Altogether about 240 m of core was recovered from 5 boreholes. After the extraction of the core, it was laid on special tables, cleaned, described and sampled. The core material was divided into four categories: for geosciences (AWI-Potsdam), biosciences (AWI-Potsdam), geochemistry (immediate processing) and geochronology (AARI-St.-Petersburg). The samples were labeled and packed in thermo-insulating boxes. These boxes were covered with snow (to maintain relatively stable temperature conditions). All samples were transported frozen to Tiksi by helicopter and then to Moscow, St. Petersburg and Germany.

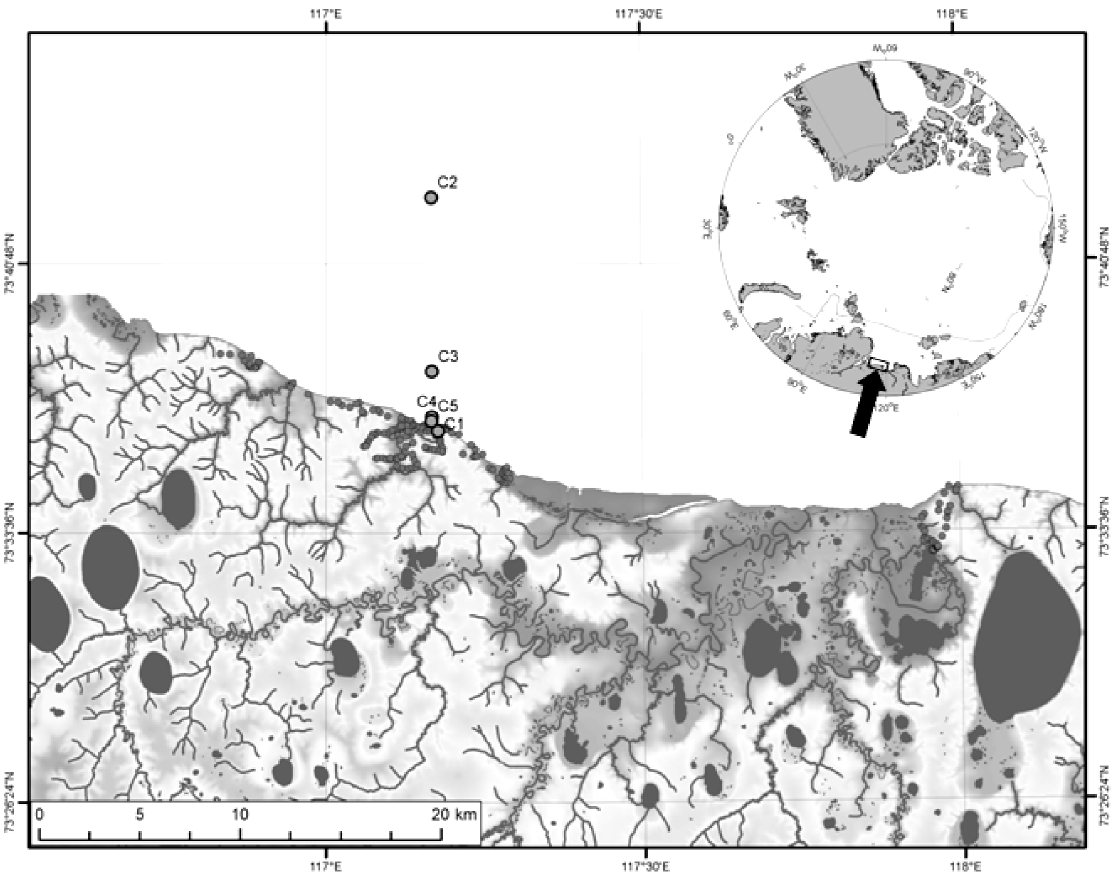

Figure 4: Cape Mamontov Klyk and borehole locations (map G. Grosse)

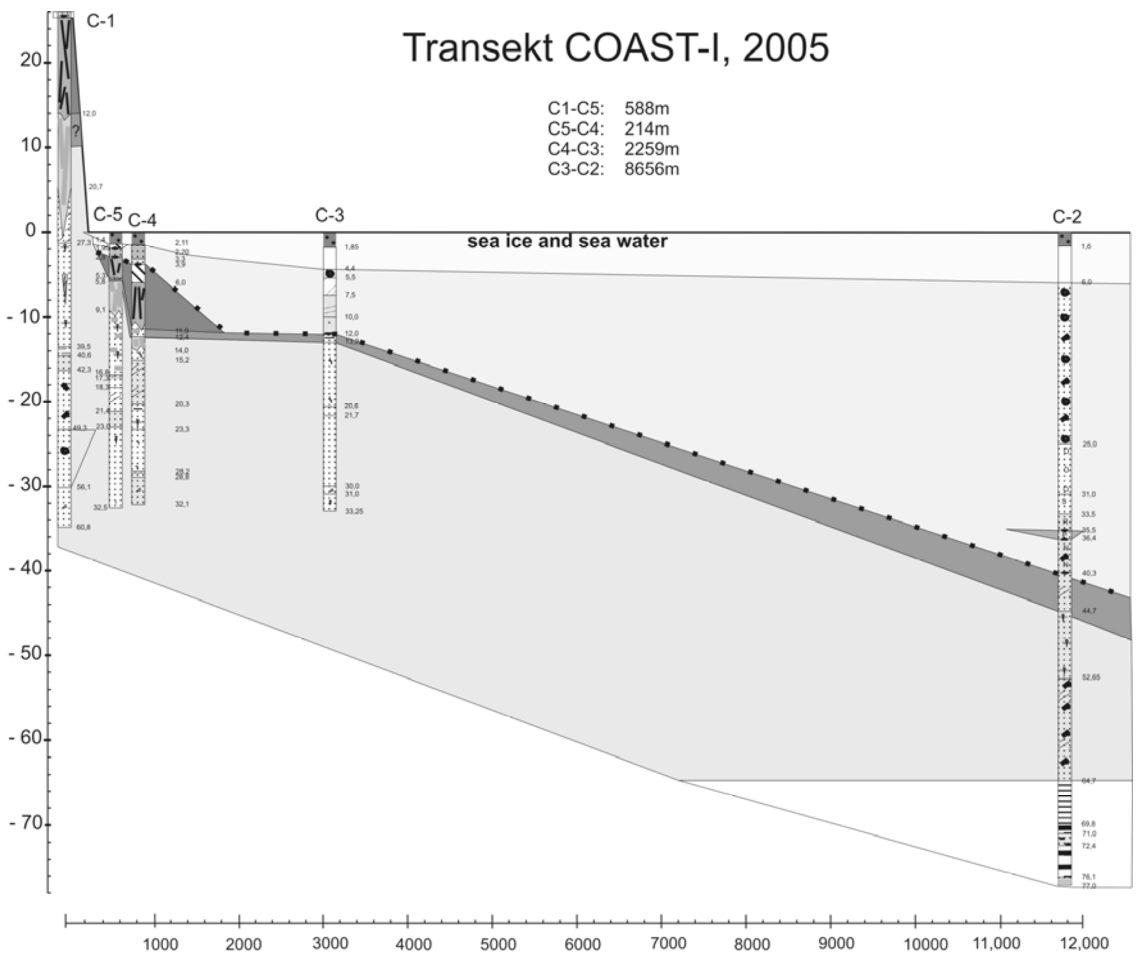

Figure 5: Schematic of drilling transect (not to horizontal scale), with coarse lithological classification. Details on the lithology are given in Figures 6 to 10.

The expedition resulted in 5 cores (Figure 5 and Tables 4 to 7). The borehole profile was located along a line of longitude (approximately 117 ° 10' E) in the Cape Mamontov Klyk area, from the coastal zone to the north. Core 1 (C-1) was drilled on the mainland at a distance of approximately 100 m from the coastline and reached a depth of approximately 60 m. Core 1 contained exclusively frozen, terrestrial, permafrost-affected material. It serves as reference material for terrestrial permafrost unaffected by transgression or direct erosion. A temperature string was installed in the borehole after drilling and permafrost temperatures have been recorded since the time of drilling [editor's note: a complete year of temperature data was recovered in the summer of 2006, and measurements continue]. The results will contribute to the international measuring network for the collection of permafrost temperatures (the Global Terrestrial Network for Permafrost, GTN-P).

Table 4: Borehole coordinates.

Borehole	Latitude	Longitude
Borehole C-1	73° 36’ 21.5" N	117° 10’ 38.5" E
Borehole C-2	73°42’ 36.1" N	117° 10’ 01.1" E
Borehole C-3	73° 37’ 56.8" N	117° 10’ 04.4" E
Borehole C-4	73° 36’ 43.9" N	117° 10’ 02.1" E
Borehole C-5	73° 36’ 37.0" N	117° 09’ 59.8" E

Table 5: Time-table of drilling process

Borehole	Date(s)
Borehole C-1	12.-14.04.2005
Boreholes C-2 & C-2a	14.-19.04.2005
Borehole C-3	21.-22.04.2005
Borehole C-4	22.-23.04.2005
Boreholes C-5a, C-5b, C-5c	24.-25.04.2005

Table 6: Timing of borehole temperature measurements

Borehole	Drilling completion	Measurement date		
C-1	14.04.2005	14.04.2005	21.04.2005	25.04.2005
C-2	19.04.2005	20.04.2005	26.04.2005	
C-3	20.04.2005	26.04.2005		
C-4	22.04.2005	26.04.2005		
C-5	25.04.2005	26.04.2005		

Table 7: Overview of the core material recovered on the COAST expedition.

	C-1	C-2	C-3	C-4	C-5
Distance to coast [km]	0.1	11.5	3	1	0.5
Water depth [m]	-	6.0	4.4	2.2	1.5
Ice thickness [m]	-	1.35	1.85	2.1	1.5
Bottom water salinity [‰]	-	29.2	30.0	32.2	> 100
Bottom water temperature [°C]	-	-1.54	-1.61	-1.67	-5 to -7
Frost table depth [m]	0	35	12	3.9	2.8

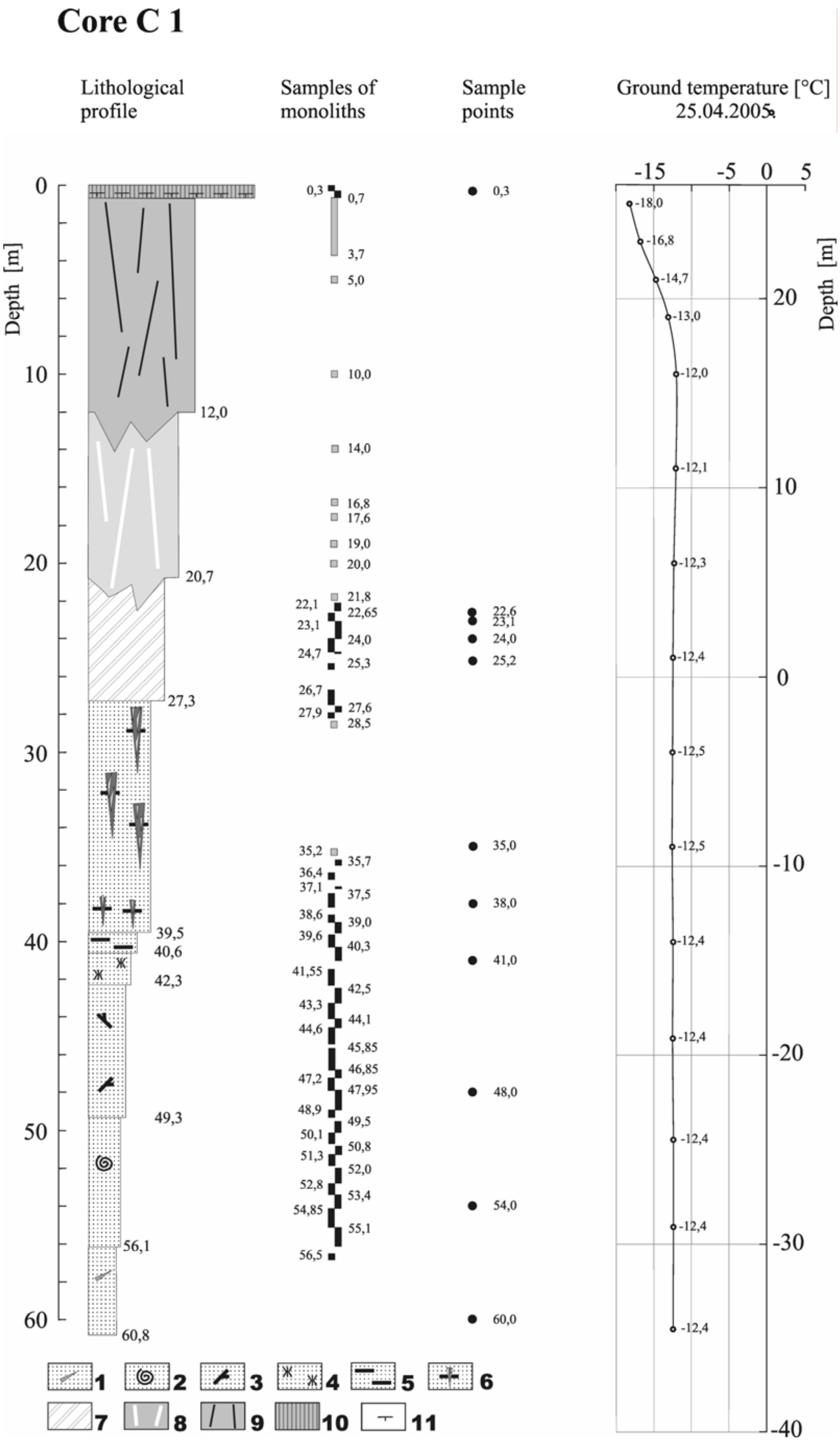

Figure 6: Core C-1 lithology, sample points and temperature profile

Table 8: Legend for the lithological profile of core C-1.

#	Depth [m]	Sediment	Cryotexture
11.		Active layer (seasonally thawing layer) boundary	
10.	0.3-0.7	Loam (clayey-silty and fine sand), dark gray, silty with layers and lenses of dark gray autochthonous peat	0.4-0.7 m lens-like cryotexture; lens-like (upper profile) to network-like
9.	0.7 – 12.7	Ice light gray, ice wedge, layered, with stains of gray and black sediment (mud) with vertical lines of small gas bubbles (1-2 mm)	
8.	2.7 – 20.7	Ice, brownish gray, ice wedge, layered, with vertical lines of small gas bubbles (1-2 mm) and bands of brown sediment	
7.	20.7 – 27.3	Fine sand, light gray, in horizontal and inclined layers; individual horizontal interbeds enriched with grass roots; many roots at the boundary between the lower portion of the gray layer containing spots and streaks– fragments of paleosoil.	Ice-bonded
6.	27.3 – 39.5	Fine sand, light gray,	Interspersed ice layers (1-2 cm); fragments of composite ice wedges (Polosatiki); Ice-bonded
5.	39.5 – 40.6	Mostly fine sand, light gray,	Individual horizontal interbeds of ice (up to 10 cm thick), massive, Ice-bonded
4.	40.6 – 42.3	Sand brownish gray (reddish), fine to medium grain size with horizontal layering.	Massive, ice-bonded.
3.	42.3 – 49.3	Fine sand, dark gray, with interbeds of fine sand, mostly horizontally layered; thin(2 mm) lenses of brown and dark gray plant detritus.	Massive, ice-bonded.
2.	43.3 – 56.1	Fine sand, dark gray, with interbeds of fine sand, mostly horizontal layered, fragments of small thin-walled shells, fine lenses with black organic material (> 49.3 m).	Massive, ice-bonded
1.	56.1 – 60.8	Fine sand, dark gray, with interbeds of fine sand (clayey-silty and fine sand), mostly horizontally layered, individual inclusions of small (3-4 cm) quartz grit (at 57.3 m).	Massive, ice-bonded

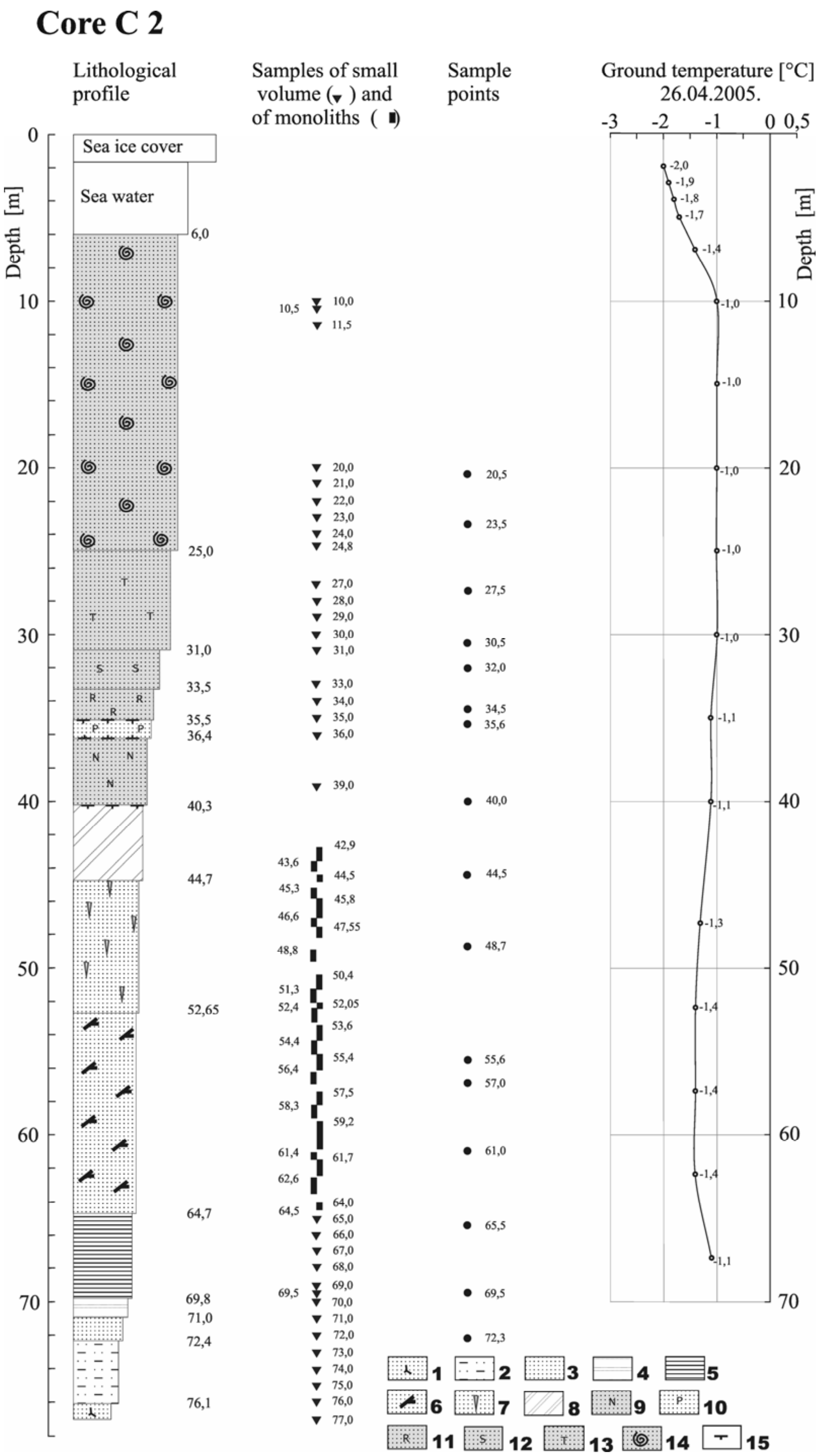

Figure 7: Core C-2 lithology, sample points and temperature profile

Table 9: Legend for the lithological profile of core C-2

no	Depth [m]	Sediment	Cryotexture
15.		The boundary of frozen, ice-bearing sediment; vertical mark is oriented towards the frozen layers	
14.	6.0 – 25.0	Fine sand dark gray, with silty interlayers, lightly compressed, moist, small wood fragments (0.5–5 mm), individual double shells < 2 mm	Unfrozen
13.	25.0 - 31.0	Fine sand dark gray, lightly compressed, moist	Unfrozen
12.	31.0 – 33.5	Fine sand dark gray, thin layers of silty, fine sand, lightly compressed, moist	Unfrozen
11.	33.5 – 35.5	Fine sand, brownish gray thin layers of silty fine sand, dense, moist	Unfrozen
10.	35.5 – 36.4	Silty fine sand, brownish gray (upper), dark gray (lower), small black spots	Frozen, ice-bonded
9.	36.4 – 40.3	Fine sand brownish gray, light (straw yellow), small wood fragments (0.5–5mm), wet and viscous	Unfrozen
8.	40.3 – 44.7	Clayey fine sand, brownish gray, horizontal and inclined layering.	Frozen, ice-bonded
7.	44.7 – 52.65	Fine sand brownish gray, interbeds of light gray: thin almost black lenses of plant remains	Fragments of ice wedges (Polosatiki), ice-bonded, interbeds with lenses – up to network-like (at 49.1–49.3; 49.6–49.7; 49.9–50.2 m) and basal cyrotexture (at 49.0–49.1; 49.7–49.9; 52.4–52.65 m)
6.	52.65 – 64.7	Medium to fine sand, brownish gray, horizontal and inclined layering; interbeds of alluvial peat (at 62.1 – 62.3m), scattered fragments of thin twigs and wood detritus.	Ice-bonded, individual small ice lenses bordering on wood remains
5.	64.7 – 69.8	Dark gray loam, clay, individual fine sand layers	Frozen, ice-bonded
4.	69.8 – 71.0	Silty fine sand , dark gray, loamy interbeds	Frozen, ice-bonded
3.	71.0 – 72.4	Fine sand, brownish gray, thin silt interbeds	Frozen, ice-bonded
2.	72.4 – 76.1	Silty fine sand (Aleurit) dark gray, with loamy and fine sand interlayers; gravel (D 1 cm) at 75.5 m depth	Ice-bonded (?)
1.	76.1 – 77.0 (0.9 m)	Fine sand, brownish gray, gray-blue sand-interbeds with horizontal layering	Frozen, ice-bonded

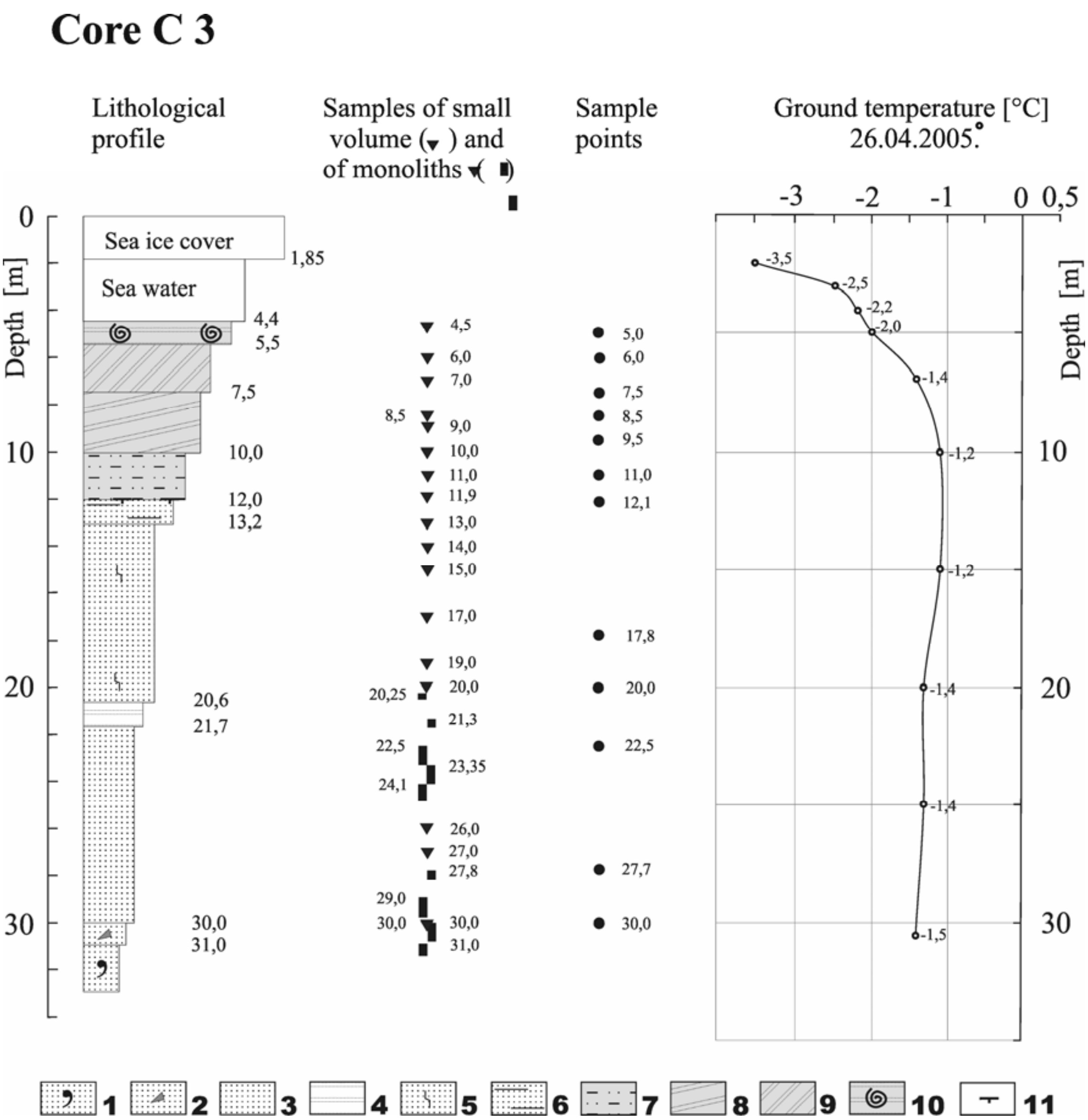

Figure 8: Core C-3 lithology, sample points and temperature profile

Table 10. Legend for the lithological profile of core C-3

no	Depth [m]	Sediment	Cryotexture
11.		Permafrost boundary	
10..	4.4 – 5.5	Aleurit dark gray, almost black, inclusions of plant detritus, fragments and complete specimens of double shells, lightly compressed, wet	Unfrozen
9.	5.5 – 7.5	Aleurit, dark gray, layered, interbeds of brownish gray aleurit, denser than overlying sediment, wet	Unfrozen
8.	7.5 – 10.0	Aleurit brownish gray, layered, sand interbeds and black aleurit, thin lenses (1-2 mm) and small inclusions (up to 3 cm) of plant detritus, wet	Unfrozen
7.	10.0 – 12.0	Fine sand, brownish gray, interbeds of dark gray aleurit, thin (1-2 mm) lenses of plat detritus, and individual small peat inclusions (up to 2 cm), moss and grass remains, wet	Unfrozen
6.	12.0 – 13.2	Fine sand, somewhat silty, brownish/blueish gray, small sparse plant remains	Frozen, ice-bonded
5.	13.2 – 20.6	Fine sand, dark gray fine-grained, and thin-grained, mostly horizontally layered, individual roots (at 15.4 -17.8 m), small peat inclusions (at 13.2 – 15.4 m and 19.6 – 20.6 m)	Frozen, ice-bonded
4.	20.6 – 21.7	Fine sand light gray, brownish gray in places, horizontal layering	Frozen, ice-bonded
3.	21.7 – 30.0	Fine sand light gray, horizontal layering, aleurit interbeds (transforms into quicksand on melting)	Frozen, ice-bonded
2.	30.0 – 31.0	Fine sand gray, layered, individual quartz gravel and pebbles (up to 2 cm)	Frozen, ice-bonded
1.	31.0 – 33.25 thickness 2.25 m	Fine sand gray, layered, small peat inclusions (up to 1 cm), black sulphide spots	Frozen, ice-bonded

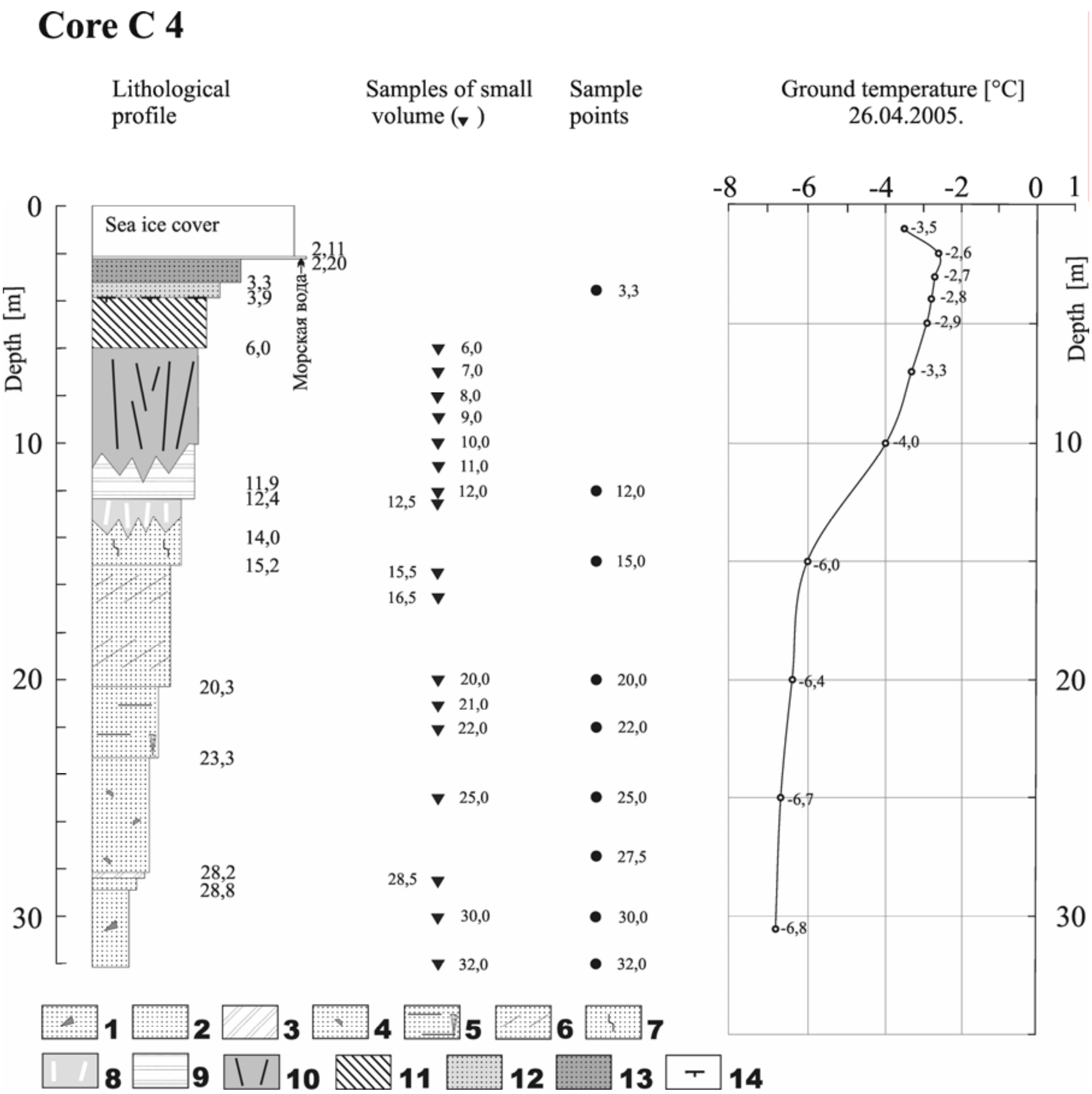

Figure 9: Core C-4 lithology, sample points and temperature profile

Table 11: Legend for the lithological profile of core C-4

no	Depth [m]	Sediment	Cryotexture
14.		Permafrost boundary	
13.	2.2 – 3.3	Fine sand dark gray, silty, with individual interbeds of gray sand and inclusions of dark spots and of fine plant detritus	Unfrozen
12.	3.3 -3.9	Fine sand, brownish gray, inclusions of plant remains	Unfrozen
11.	3.9 -6.0	Loam, dark gray, with inclusions of plant remains (detritus), dense.	Frozen, ice-cemented
10.	6.0 – 11.9		Ice, gray and opaque, vertically striped, ice wedge with gas bubbles and individual bands of brown and gray silt.
9.	11.9 – 12.4	Fine sand, silty, dark gray, horizontally layered.	contains roots of ice wedges, ice-cemented
8.	12.4 – 14.0		Ice wedge, yellowish gray, vertically striped, with gas bubbles and with many brown silt and sand stripes (Polosatik).
7.	14.0 – 15.2	Fine sand, silty, green-gray, horizontally layered	Frozen, ice-cemented
6.	15.2 – 20.3	Fine sand brownish gray, with horizontal and inclined layers with individual thin interbeds of aleurit and brown plant detritus (up to 3 mm).	Frozen, ice-cemented
5.	20.3 – 23.3	Fine sand, brownish gray and dark gray, mostly horizontally layered, individual interbeds of aleurit and small inclusions and lenses of grass-moss-peat (at 20.8 – 21.6 m)	Individual narrow sand-ice veins; ice wedges (Polosa-tiki), ice-cemented
4.	23.3– 28.2	Sand light gray, dark sulphide spots (at 23.3 – 24.0 m); brownish gray fine sand with occasional gravel	Frozen, ice-cemented
3.	28.2 – 28.6	Aleurit, (black, sand interbeds, frequent inclusions of plant detritus	Ice-cemented, thin ice stripes
2.	28.6 – 28.8	Fine to medium sand, gray, individual horizontal brown sand layers	Frozen, ice-cemented
1.	28.8 – 32.1	Fine sand brownish gray, individual gravel inclusions; thickness 2.1 m	Frozen, ice-cemented

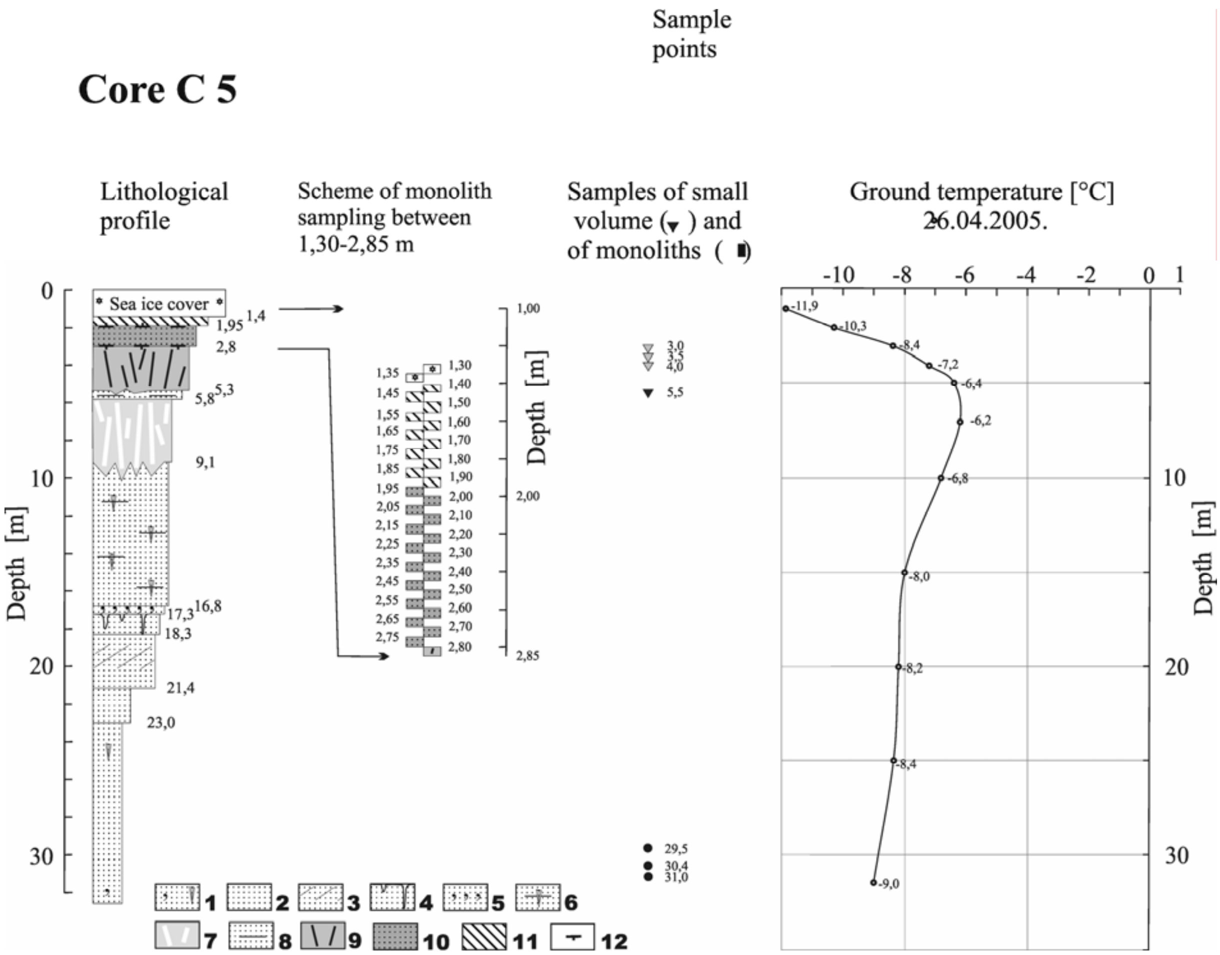

Figure 10: Core C-5 lithology, sample points and temperature profile

Table 12. Legend for the lithological profile of core C-5

no	Depth [m]	Sediment	Cryotexture
12.		Permafrost boundary	
11.	1.4 – 1.95	Aleurit dark gray	Frozen, ice-bonded
10.	1.95 – 2.8	Fine sand dark gray, with aleurit,	Unfrozen, wet
9.	2.8 – 5.3		Ice wedge brownish gray, vertically striped, with Gas bubbles and small admixtures of brown silt.
8.	5.3 – 5.8	Fine sand brownish gray, silty interbeds	Ffrozen, ice-bonded
7.	5.8 – 9.1		Ice wedge yellowish gray, vertically striped, with gas bubbles; stripes of brown fine sand (Polosatik)
6.	9.1 – 16.8	Fine sand, dark gray to brownish gray, mostly horizontally layered, individual interbeds (up to 1 cm) of aleurit.	Frozen, ice-bonded individual layers with bands of ice (at12.2 – 12.8 m), fragments of sand–ice–veins (Polosatiki) (at 9.1– 10 m; 13.7–14.5 m)
5.	16.8 – 17.3	Fine sand brown, with plant detritus (sandy peat) of grass and moss remains.	Frozen, ice-bonded
4.	17.3 – 18.3	Fine sand light gray, layered at an incline, with brown streaks of the base of the overlying layer.	Frozen, ice-bonded
3.	18.3 – 21.4	Fine to medium sand, light gray, in horizontal and inclined layers; thin inclined lenses (1– 3 mm) of fine (powder-like) plant detritus	Frozen, ice-bonded
2.	21.4 – 23.0	Fine sand brownish gray, horizontally layered	Frozen, ice-bonded
1.	23.0 – 32.5	Fine sand, brownish-bluish gray, with sulphide spots, individual interbeds of aleurit and a few thin (up to 0.2 m) lenses of alluvial peat (at 31.9 – 32.1 m), horizontally layered.. Thickness: 9.5 m	Frozen, ice-bonded network-like cryogenic texture in the upper portion (at 23.0 – 23.3 m); few vertical ice veins (at 24.1 – 26.0 m)

The subsequent 4 cores were drilled from the sea ice through submarine and ancient terrestrial deposits. The core located furthest from the coastline (Core 2 at 11.5 km from the coast) was drilled in approximately 6 m water depth with a sea ice thickness of 1.35 m. The shallow water is a reflection of the shallowness of the offshore coastal shelf in general in this region. At a depth of approximately 35 m below sea level core 2 encountered frozen submarine material (Figure 5), although, as shown later, most of the core had temperatures of less than 0 °C. Between cores C-1 and C-2 additional cores were recovered. An overview of their distribution and depths is shown in Tables 4 to 7.

Core material recovery rates were not 100% for all five cores. For additional reasons, existing sample material falls short of the total recovered material (about 240 m):

- part of the sub-sea unfrozen core was lost during drilling, sampling and processing due to its viscosity;
- part of the sub-sea unfrozen and frozen core was used for field analysis of cryogenesis and pore water chemistry. In the latter case, pressed and dried sediment was recovered and retained;
- part of the frozen core was composed of ice-wedge material that was destroyed and mixed in the well tube/core barrel on drilling, a common problem for this type of material;
- part of the contiguously frozen cores between boreholes C-3 and C-5, which were located quite close to each other, was sampled at intervals instead of completely in order to save on shipping and analyses.

The total weight of core material shipped from the field was about 1 ton. A portion of the core material (about 100 kg) was transported to AARI (St.-Petersburg). The rest of the frozen sediments were packed for transport immediately after being described lithologically and geocryologically. They were shipped frozen to Bremerhaven, Germany and archived there. Unfrozen core sections were divided into sub-samples in the field, which were then also frozen for shipping.

3.2 Pore water analyses

Some sub-samples from the unfrozen core sections were used for field analysis of pore water chemistry. Pore water was pressed from the sediments using nitrogen (Figure 11). Extracted pore water volumes varied between 2 and 15 ml per sample. These samples were collected for major cation and anion analyses in the laboratory of AWI, Potsdam using inductively coupled plasma optical emission spectroscopy (ICP-OES) and gas chromatography, respectively. The salinity reported here was calculated based on sample Cl^- and Na^+ concentrations.

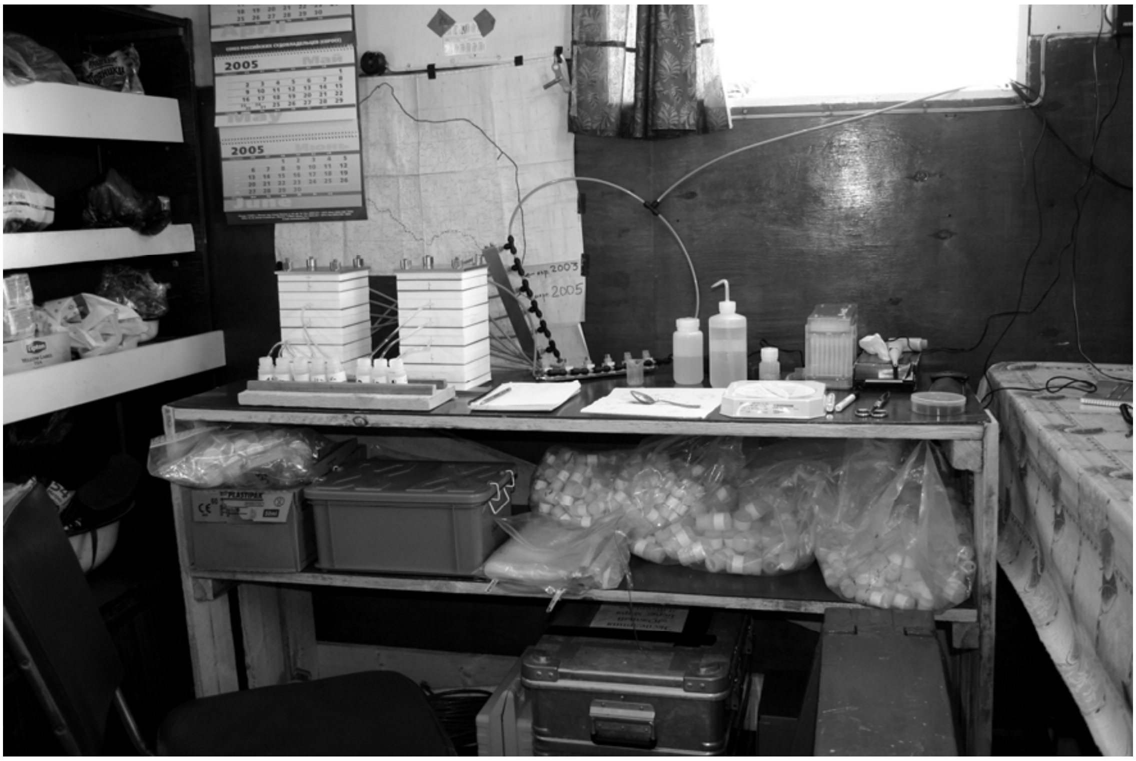

Figure 11: Pore water press in use in the field to extract sediment pore water

Figure 12: Detail photograph of core C-2 taken in the field. Although recovered from a submarine environment, ice-rich, terrestrial cryogenic structures are visible, indicating the occurrence marine transgression and/or coastal erosion

The salinity results clearly show that relict terrestrial permafrost continues over the near-shore range of the Laptev Sea continental shelf and is present there as submarine permafrost. Frozen sediments were found in all marine cores, with geocryological characteristics corresponding to those of the terrestrial permafrost encountered in core C-1. Figure 12 shows a photograph of a section of core C-2, originating from a depth of approximately 40 m below sea level. The terrestrial origin of the material's geocryological texture is corroborated by the chemical and isotope composition of the pore ice, which also correspond to those of the terrestrial permafrost of core C-1 as well as additional samples of the coastal section sampled in 2003.

Results of pore water analyses together with lithological profiles are represented in figures 13 and 14. Bottom water salinities of cores C-2 to C-4 are clearly marine and continue into the pore water of the unfrozen sediments. Pore water salinity decreases with the transition from unfrozen to frozen material, reaching almost fresh water conditions in the latter.

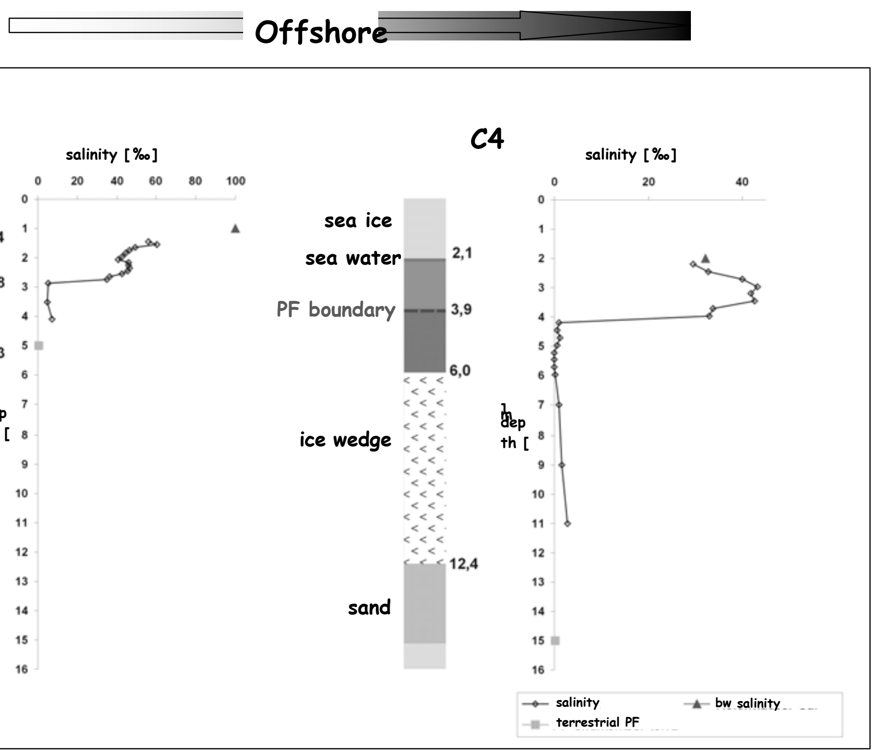

Figure 13: Lithology and salinity profiles of the cores C-4 and C-5. The position of the ice-bonded sediment table is indicated by a dashed line. The triangle marks the salinity of the bottom water and the square the salinity of the terrestrial permafrost pore water (measured in terrestrial permafrost at the Cape Mamontov Klyk).

Core 5 presents an exception in that no liquid seawater was present between the sea ice and the frozen sediment. With a total water depth 1.5 m, the sea ice lay directly on the sea bottom and was frozen to the sediment. However, water with a salinity of more than 100‰ and temperatures in the range -5 to -7 °C exuded from a number of drillings made in the region of core C-5. Ice formation results in the exclusion of salts from the freezing solution and the resultant concentration of salts in the residual solution (brine). As a result, a 1 m thick layer of unfrozen sediment was encountered directly beneath the sea ice (Figure 10, 13, Table 12). The term submarine cryopeg is applied to this layer.

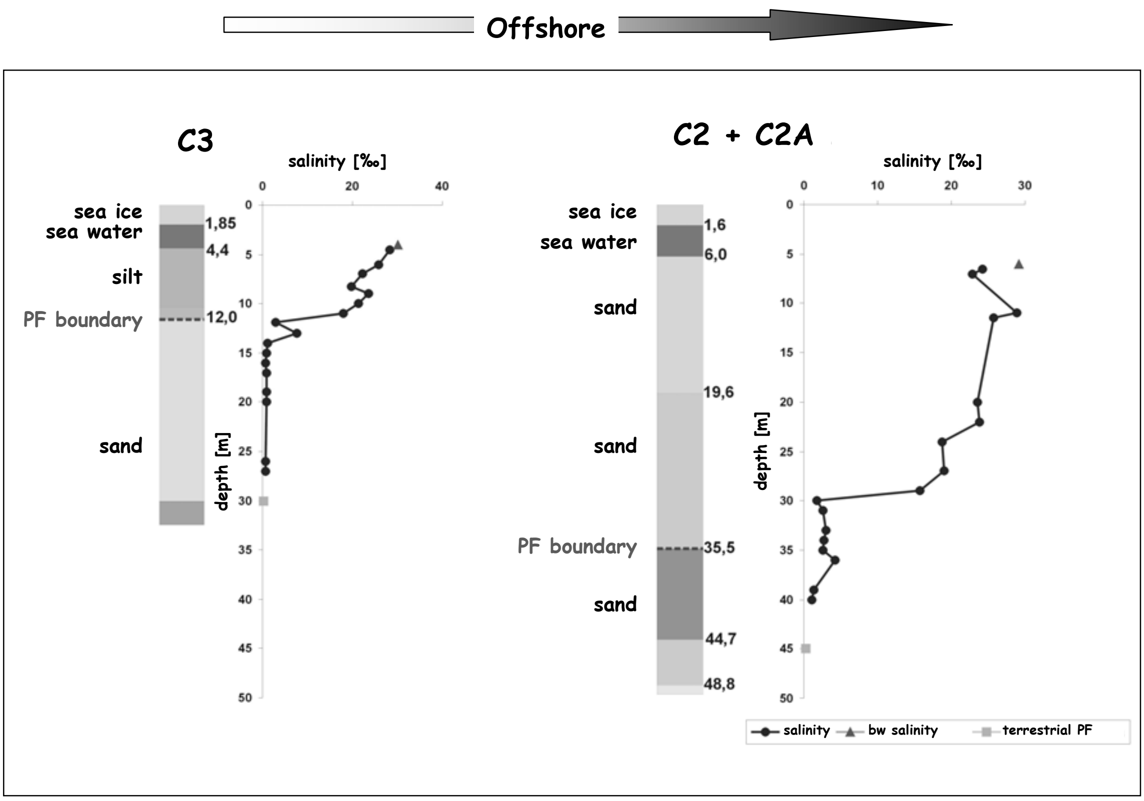

Figure 14: Lithology and salinity profiles of the cores C-2 and C-3. The position of the ice-bonded sediment table is indicated. The triangle marks the salinity of the bottom water and the square the salinity of the terrestrial permafrost pore water (measured in terrestrial permafrost at the Cape Mamontov Klyk).

The most interesting result of the drilling campaign was found in the lower section of Core 2. The lower limit of frozen material was reached at 65 m below sea level, below which an unfrozen layer was encountered (Fig 4). According to published models of permafrost distribution, permafrost thickness within the coastal range lies in the hundreds of meters. The sedimentology and pore water salinity suggest that the underlying unfrozen material is composed of marine sediments. The marine salinity levels result in an unfrozen state despite temperatures from -1 to -1.5 °C.

3.3 Temperature profiles

The thermal state of the sediment was measured at each borehole using two methods. The first method was based on resistance measurements of calibrated thermistors (MMT-4). The second device was a newly developed non-contact (infrared) temperature sensor. Measurements were made from 1 to 11 days after drilling. Both methods were used at C-1 and C-2 to compare results. To allow for equilibration of the temperature field after drilling, temperature profiles were measured at the end of the drilling campaign in boreholes C-1, C-3 and C-5, using the infrared method. Water infiltrated the other boreholes, preventing use of the infrared method at the end of the campaign.

The most prominent feature of the temperature data is the quick equilibration of submarine permafrost to the sea-water temperature (-1.5°C) and the rapid degradation that this implies. Borehole C-3 is located approximately 2500 meters off shore, which represents submergence at the local rate of coastal retreat of some 600 years before present using an estimated coastal retreat of 4 m yr^{-1}. After this short period of time the freshwater pore ice in the submarine permafrost is very close to its melting point and therefore pore water salinity becomes more important to determine the presence of ice in the submarine sediments.

Furthermore, the occurrence of unfrozen sediments in the near-shore area due to high pore water salinity and sediment temperatures raises the question whether submarine permafrost can have been preserved throughout the vast areas of the Laptev Sea shelf since last transgression.

4. Sample lists

Table 13. Sediment sample list. Field descriptions integrated in this list distinguish only the presence or absence of ice wedges. Many samples are labeled with a single depth only; in general, these are samples which are not included in the AWI sample set, which total 54 m of sediment material from the total 235.55 m of drilled sediment depth.

Sample Number	Core Number	Upper Depth	Lower Depth	Description
1	C-1	0.00	0.30	sediment
2	C-1	0.32	0.70	sediment
3	C-1	0.70	3.70	sediment with ice wedges
4	C-1		5.00	sediment with ice wedges
5	C-1		10.00	sediment with ice wedges
6	C-1		14.00	sediment with ice wedges
7	C-1		16.80	sediment with ice wedges
8	C-1		17.60	sediment with ice wedges
9	C-1		19.00	sediment with ice wedges
10	C-1		20.00	sediment with ice wedges
11	C-1		21.80	sediment with ice wedges
12	C-1	22.10	22.60	sediment
13	C-1	22.65	23.10	sediment
14	C-1	23.10	24.00	sediment
15	C-1	24.00	24.70	sediment
16	C-1	24.70	24.75	sediment
17	C-1	25.30	25.60	sediment
18	C-1	26.70	27.50	sediment
19	C-1	27.60	27.90	sediment
20	C-1	27.90	28.20	sediment with ice layer
21	C-1		30.30	sediment with ice wedges
22	C-1		35.20	sediment with ice wedges
23	C-1	35.70	36.00	sediment
24	C-1	36.40	36.70	sediment
25	C-1	37.10	37.20	ice-rich sediment
26	C-1	37.50	38.20	sediment
27	C-1	38.60	39.00	sediment
28	C-1	39.00	39.50	sediment
29	C-1	39.60	40.30	sediment
30	C-1	40.30	41.00	sediment
31	C-1	41.55	42.30	sediment
32	C-1	42.50	43.30	sediment
33	C-1	43.30	44.10	sediment
34	C-1	44.10	44.60	sediment

Table 13. Continuation

Sample Number	Core Number	Upper Depth	Lower Depth	Description
35	C-1	44.60	45.50	sediment
36	C-1	45.85	46.85	sediment
37	C-1	46.85	47.20	sediment
38	C-1	47.20	47.95	sediment
39	C-1	47.95	48.90	sediment
40	C-1	48.90	49.30	sediment
41	C-1	49.50	50.10	sediment
42	C-1	50.10	50.70	sediment
43	C-1	50.80	51.30	sediment
44	C-1	51.30	51.90	sediment
45	C-1	52.00	52.80	sediment
46	C-1	52.80	53.40	sediment
47	C-1	53.40	54.10	sediment
48	C-1	54.85	55.10	sediment
49	C-1	55.10	56.10	sediment
50	C-1	56.50	56.80	sediment
51	C-1	56.80	57.70	sediment
52	C-1	57.80	58.50	sediment
53	C-1	58.55	59.30	sediment
54	C-1	59.35	60.00	sediment
55	C-1	60.00	60.80	sediment
30	C-2A		6.00	sediment
31	C-2A		6.50	sediment
32	C-2A		7.00	sediment
54	C-2A		6.00	sediment
55	C-2A		6.50	sediment
56	C-2A		7.00	sediment
33	C-2A		11.50	sediment
56	C-2A		11.50	sediment
32	C-2		10.00	sediment
33	C-2		10.50	sediment
5	C-2		10.50	sediment
6	C-2		11.50	sediment
7	C-2		11.50	sediment
38	C-2		20.00	sediment
9	C-2		20.00	sediment
10	C-2		21.00	sediment
11	C-2		21.00	sediment
12	C-2		22.00	sediment

Table 13: Continuation

Sample Number	Core Number	Upper Depth	Lower Depth	Description
13	C-2		22.00	sediment
14	C-2		23.00	sediment
15	C-2		23.00	sediment
16	C-2		24.00	sediment
17	C-2		24.00	sediment
18	C-2		24.80	sediment
19	C-2		24.80	sediment
20	C-2		27.00	sediment
21	C-2		27.00	sediment
22	C-2		28.00	sediment
23	C-2		28.00	sediment
24	C-2		29.00	sediment
25	C-2		29.00	sediment
26	C-2		30.00	sediment
27	C-2		30.00	sediment
28	C-2		31.00	sediment
29	C-2		31.00	sediment
30	C-2		33.00	sediment
31	C-2		33.00	sediment
32	C-2		34.00	sediment
33	C-2		34.00	sediment
34	C-2		35.00	sediment
35	C-2		35.00	sediment
36	C-2		36.00	sediment
37	C-2		36.00	sediment
38	C-2		39.00	sediment
39	C-2		39.00	sediment
32	C-2	40.00	40.30	sediment
33	C-2	40.30	41.00	sediment
34	C-2	41.10	41.90	sediment
35	C-2	42.10	42.70	sediment
36	C-2	42.90	43.50	sediment
37	C-2	43.60	44.20	sediment
38	C-2	44.50	44.80	sediment
39	C-2	45.30	45.80	sediment
40	C-2	45.80	46.60	sediment
41	C-2	46.60	47.55	sediment
42	C-2	47.55	48.25	sediment
43	C-2	48.80	49.60	sediment

Table 13: Continuation

Sample Number	Core Number	Upper Depth	Lower Depth	Description
44	C-2	50.40	51.30	sediment
45	C-2	51.30	52.05	sediment
46	C-2	52.05	52.40	sediment
47	C-2	52.40	53.40	sediment
48	C-2	53.60	54.40	sediment
49	C-2	54.40	55.40	sediment
50	C-2	55.40	56.20	sediment
51	C-2	56.40	57.20	sediment
52	C-2	57.50	58.30	sediment
53	C-2	58.30	59.10	sediment
54	C-2	59.20	61.10	sediment
55	C-2	61.40	61.70	sediment
56	C-2	61.70	62.50	sediment
57	C-2	62.60	63.50	sediment
58	C-2	64.00	64.50	sediment
59	C-2		65.00	sediment
60	C-2		65.00	sediment
61	C-2		66.00	sediment
62	C-2		66.00	sediment
63	C-2		67.00	sediment
64	C-2		67.00	sediment
65	C-2		68.00	sediment
66	C-2		68.00	sediment
67	C-2		69.50	sediment
68	C-2		69.50	sediment
69	C-2		70.00	sediment
70	C-2		70.00	sediment
71	C-2		71.00	sediment
72	C-2		71.00	sediment
73	C-2		72.00	sediment
74	C-2		72.00	sediment
75	C-2		73.00	sediment
76	C-2		73.00	sediment
77	C-2		74.00	sediment
78	C-2		74.00	sediment
79	C-2		75.00	sediment
80	C-2		75.00	sediment
81	C-2		76.00	sediment
82	C-2		76.00	sediment

Table 13: Continuation

Sample Number	Core Number	Upper Depth	Lower Depth	Description
83	C-2		77.00	sediment
84	C-2		77.00	sediment
85	C-3		4.50	sediment
86	C-3		6.00	sediment
87	C-3		7.00	sediment
88	C-3		8.50	sediment
89	C-3		9.00	sediment
90	C-3		10.00	sediment
91	C-3		11.00	sediment
92	C-3		11.90	sediment
93	C-3		13.00	sediment
94	C-3		14.00	sediment
95	C-3		15.00	sediment
96	C-3		17.00	sediment
97	C-3		19.00	sediment
98	C-3		20.00	sediment
99	C-3	20.25	20.60	sediment
100	C-3	21.30	21.70	sediment
101	C-3	22.50	23.35	sediment
102	C-3	23.35	24.10	sediment
103	C-3	24.10	24.80	sediment
104	C-3		26.00	sediment
105	C-3		27.00	sediment
106	C-3	27.80	28.30	sediment
107	C-3	29.00	29.80	sediment
108	C-3		30.00	sediment
109	C-3	30.20	30.90	sediment
110	C-3	31.00	31.50	sediment
111	C-3		4.50	sediment
112	C-3		6.00	sediment
113	C-3		7.00	sediment
114	C-3		8.50	sediment
115	C-3		9.00	sediment
116	C-3		10.00	sediment
117	C-3		11.00	sediment
118	C-3		11.90	sediment
119	C-3		13.00	sediment
120	C-3		14.00	sediment
121	C-3		15.00	sediment

Table 13: Continuation

Sample Number	Core Number	Upper Depth	Lower Depth	Description
122	C-3		17.00	sediment
123	C-3		19.00	sediment
124	C-3		20.00	sediment
125	C-3		26.00	sediment
126	C-3		27.00	sediment
127	C-3		30.00	sediment
128	C-4		6.00	sediment
129	C-4		7.00	sediment
130	C-4		8.00	sediment
131	C-4		9.00	sediment
132	C-4		10.00	sediment
133	C-4		11.00	sediment
134	C-4		12.00	sediment
135	C-4		12.50	sediment
136	C-4		15.50	sediment
137	C-4		16.50	sediment
138	C-4		20.00	sediment
139	C-4		21.00	sediment
140	C-4		22.00	sediment
141	C-4		25.00	sediment
142	C-4		28.50	sediment
143	C-4		30.00	sediment
144	C-4		32.00	sediment
145	C-4		12.00	sediment
146	C-4		15.50	sediment
147	C-4		16.50	sediment
148	C-4		20.00	sediment
149	C-4		21.00	sediment
150	C-4		22.00	sediment
151	C-4		25.00	sediment
152	C-4		28.50	sediment
153	C-4		30.00	sediment
154	C-4		32.00	sediment
155	C-5	1.50	1.55	sediment
156	C-5	1.60	1.65	sediment
157	C-5	1.70	1.75	sediment
158	C-5	1.80	1.85	sediment
159	C-5	1.90	1.95	sediment
160	C-5	2.00	2.05	sediment

161	C-5	2.10	2.15	sediment
162	C-5	2.20	2.25	sediment
163	C-5	2.30	2.35	sediment
164	C-5	2.40	2.45	sediment
165	C-5	2.50	2.55	sediment
166	C-5	2.60	2.65	sediment
167	C-5	2.70	2.75	sediment
168	C-5	2.80	2.85	sediment
169	C-5	2.90	2.95	sediment
170	C-5		3.00	sediment with ice wedges
171	C-5		5.50	sediment with ice wedges

Table 14. Pore water samples recovered hydraulically from cored sediments in the field, with field-determined salinities.

Core	Depth [m]	Cations [10 ml]	Anions [15 lL]	Isotopes [30 ml]	Sediment Cakes [100 g]	Remarks	Salinity [mS/cm]	Volume [ml]
C-2	11	x	x		x			10
C-2	20	x	x		x			10
C-2	22	x	x		x			11
C-2	24	x	x		x			6
C-2	27	x	x		x			8
C-2	28				x			0
C-2	29	x	x		x			5
C-2	30	x	x		x			12
C-2	31	x	x		x			7
C-2	33	x			x			3
C-2	34	x	x		x			13
C-2	35	x	x		x	frozen	3.9	17
C-2	36	x	x		x	frozen		7
C-2	39	x			x	frozen		4
C-2	40	x	x		x	frozen		4
C-2	42			x	x	frozen	1.2	
C-2	43.5			x	x	frozen	0.9	
C-2	66-68					unfrozen mud	16.1	
C-2A	6				x			0
C-2A	6.5	x			x			3
C-2A	7	x	x					8
C-2A	11.5	x	x		x			5
C-3	4.5	x			x			3
C-3	6	x			x			2
C-3	7	x	x		x	brown		5
C-3	8.3	x			x			2
C-3	8.5				x			0
C-3	9	x			x			2
C-3	10	x			x			3
C-3	11	x	x		x	brown		12
C-3	11.9	x	x		x	frozen	3.8	8
C-3	13	x			x	frozen		4
C-3	14	x	x		x	frozen		7
C-3	15	x	x		x	frozen		14
C-3	16	x	x		x	frozen		10
C-3	17	x	x		x	frozen		13
C-3	19	x	x		x	frozen		21

Table 14: Continuation

Core	Depth [m]	Cations [10 ml]	Anions [15 lL]	Isotopes [30 ml]	Sediment Cakes [100 g]	Remarks	Salinity [mS/cm]	Volume [ml]
C-3	20	x	x		x	frozen		19
C-3	26	x	x		x	frozen		8
C-3	27	x	x		x	frozen		6
C-4	0+2.2	x	x		x			15
C-4	0.25+2.2	x	x		x			12
C-4	0.5+2.2	x	x		x			8
C-4	0.75+2.2	x			x			3
C-4	1+2.2	x			x			2
C-4	1.25+2.2	x			x			1.5
C-4	1.5+2.2	x			x			1
C-4	1.75+2.2	x			x			3
C-4	2+2.2	x	x	x		frozen/ice		
C-4	2.25+2.2	x	x	x		frozen/ice		
C-4	2.5+2.2	x	x	x		frozen/ice		
C-4	2.75+2.2	x	x	x		frozen/ice		
C-4	3+2.2	x	x	x		frozen/ice		
C-4	3.25+2.2	x	x	x		frozen/ice		
C-4	3.5+2.2	x	x	x		frozen/ice		
C-4	3.75+2.2	x	x	x		frozen/ice		
C-4	7	x	x	x		frozen/ice		
C-4	9	x	x	x		frozen/ice		
C-4	11	x	x	x		frozen/ice		
C-5	1.45	x	x		x			8
C-5	1.55	x	x		x			10
C-5	1.65	x	x		x			8
C-5	1.75	x	x		x			8
C-5	1.85	x	x		x			16
C-5	1.95	x	x		x			6
C-5	2.05	x	x		x			8
C-5	2.15	x	x		x			10
C-5	2.25	x	x		x			11
C-5	2.35	x	x		x			7
C-5	2.45	x	x		x			8
C-5	2.55	x	x		x			11

Table 14: Continuation

Core	Depth [m]	Cations [10 ml]	Anions [15 lL]	Isotopes [30 ml]	Sediment Cakes [100 g]	Remarks	Salinity [mS/cm]	Volume [ml]
C-5	2.65	x	x		x			9
C-5	2.75	x	x		x			14
C-5	2.85-2.90	x	x	x		frozen/ice		
C-5	3.5	x	x	x		frozen/ice		
C-5	4.1	x	x	x		frozen/ice		

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